Subsurface Flow Characteristics of

Recharge Pits as Determined from

A Laboratory Model

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by

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# ILLUSTRATIONS

## ABSTRACT

In order to design an efficient ground water recharge area, the movement of recharged water beneath the surface of a pit must be understood. With the aid of a model to study the water movement, certain flow characteristics were detected, figured and described. The series of experiments began with an isotropic medium and progressed through more complex tests to the final one, which consisted of several stratified layers of different sized granular material. The granular material consisted of sorted sand and gravel.

# INTRODUCTION

## SCOPE OF INVESTIGATION

The primary objective of this study was to determine some of the qualitative properties of water infiltrating into a porous body, i.e., a recharge pit. The properties could then be applied directly to the field situation, providing the field situation has been studied in sufficient detail to determine geohydrologic bounds and properties. The tests dealt only with clastic material and is analogous in the field to glacial deposits or other unconsolidated material. Even under the ideal controlled conditions of laboratory testing, patterns of movement of the wetting front can be studied and detected. It would also be possible to make quantitative measurements that could be correlated with actual field recharge conditions, provided the material was very similar.

## PREVIOUS WORK

Much work and numerous reports describe the actual field conditions under which ground water recharge areas were designed and operated. Research in the laboratory which simulates field situations, has been rather limited. The majority of this research has been under the direction of A. I. Johnson at the United States Geological Survey Hydrologic Laboratory in Denver, Colorado. Several of his publications are listed in the reference section.

## ACKNOWLEDGMENTS

I wish to thank Dr. Wayne Pettyjohn for his inspiration, thoughtful suggestions and criticism of this report. Secondly, I wish to thank Mr. Tom Carothers for his advice during the construction of the model. Also, I am grateful to the Ohio State University Department of Geology for the material and equipment used in conducting the research.

## METHODS OF INVESTIGATION

Some preliminary research of previous work on recharge models was conducted. With those facts in mind, a model was designed and built. This report parallels in some respect the previous work. But since the investigator had no knowledge of the mechanics of a recharge system, a laboratory model was chosen. With the aid of the theory of ground water movement, the experimental results (Plates I-IX) were described and some meaningful characteristics derived.

# THEORY AND DEFINITION OF TERMS

The physical forces and their interactions, as they affect ground water, can be found in any elementary text of hydrology. The following forces affect the water movement. First, the force of gravity is the predominate force and tends to pull mass upon the surface of the earth towards the center of the earth. The cohesion of the water molecules is the second important force and the adhesion of the water molecules with the surrounding rock particles is the third force. Finally the rock characteristics (grain size shape sorting and distribution, porosity, specific retention, specific yield, and permeability) determine the effect of the above mentioned forces.

Most rock contains interstices, or void spaces. The space commonly is described quantitatively by a property known as porosity. Porosity is defined as the ratio, usually expressed as a percentage, of the volume of voids of a given rock mass to the total volume of the rock mass. For all practical purposes, ground water fills all void spaces in the saturated zone. From the previous definition, therefore, it follows that porosity is a measure of the quantity of water contained per unit volume (Todd 1959).

Not all water contained in the saturated zone can be removed from the rock by drainage. Gravity ground water is that part of the water that will drain by gravity. That part of the water retained by molecular and surface tension forces in the void spaces of the rock is known as retained water. The water-yielding capacity and water-retaining capacity of rock is known as specific yield and specific retention. The specific yield plus the specific retention of a rock is equal to the porosity of the rock.

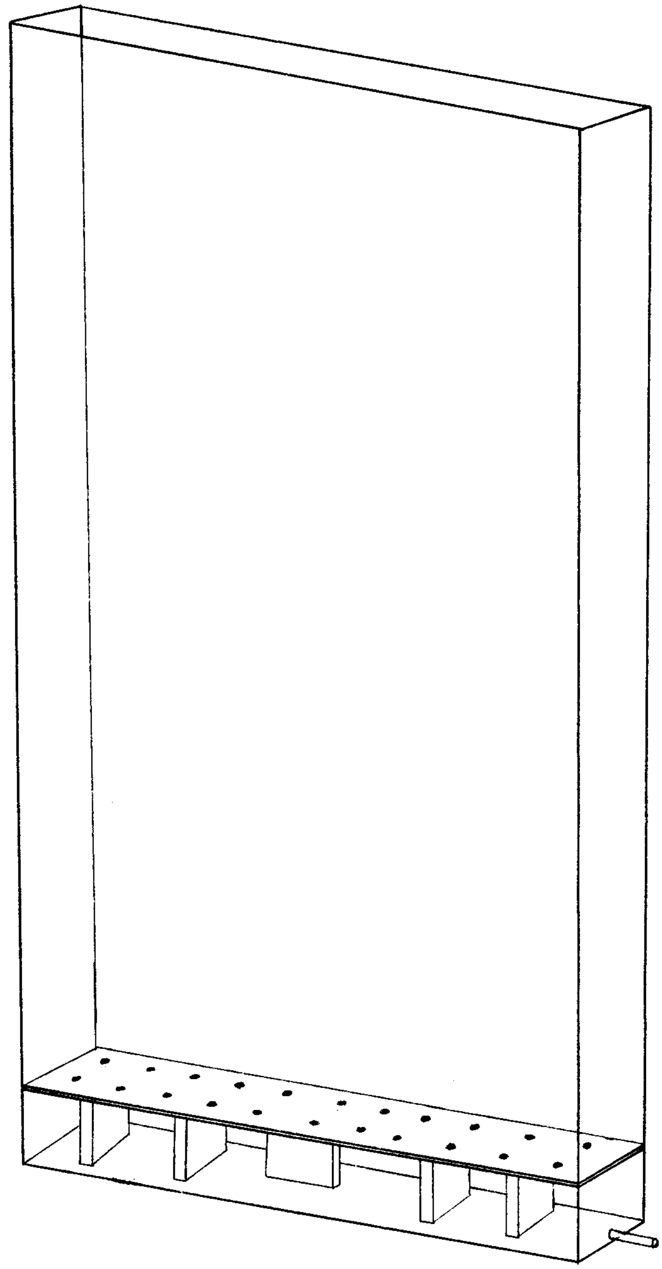
Permeability is a measure of the capacity of a material to transmit water under pressure. It may be determined in the laboratory by observing the rate of percolation of water through samples of known length and cross-sectional area under a known difference in head.

The basic law for flow of fluids through porous materials was established by Darcy, who demonstrated experimentally that the rate of flow of water was proportional to the hydraulic gradient. Darcy's law may by expressed as $Q=PIA$ in which $Q$ is the quantity of water discharged in a unit of time, $A$ is the total cross-sectional area through which the water percolates, $I$ is the hydraulic gradient, and $P$ is the coefficient of permeability of the material for water. Permeability is defined (Wenzel 1942) as the rate of flow of water in gallons per day, through a cross-sectional area of one square foot under a hydraulic gradient of one foot per foot at a temperature of $60^{\circ}F$.

## THE MODEL

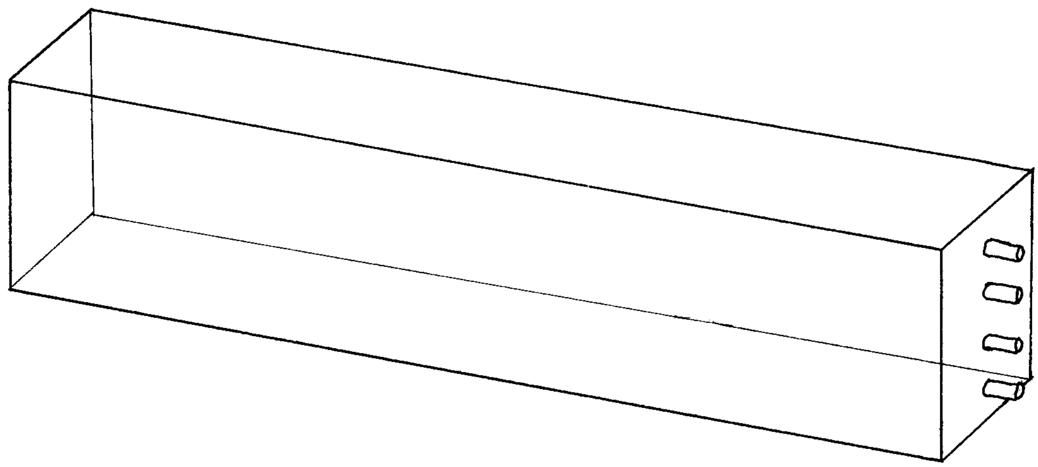
The Tank for the infiltration tests was constructed of acrylic plastic 1/2-inch thick. The inside dimensions of the model are two feet wide, four feet high, and three inches thick; with an inside volume of two cubic feet (Fig. 1). The tank was bonded together with a suitable solvent and reinforced along the bottom and sides with screws. Inside the tank, two inches above the bottom, is a 1/2-inch acrylic plastic plate. This plate is placed such that it forms a false bottom (Fig. 1). The plate contains twenty-two equally spaced drainage holes 1/4-inch in diameter. Each hole is covered by a square of fine-mesh brass screen to prevent loss of granular material during testing. The perforated plate, along with the bottom part of the tank, forms a drainage collection tank for water after it filters through the material in the model. Vertical supports within the collection tank prevent cave-in or slippage of the perforated plate.

A small reservoir tank was constructed of 1/4-inch acrylic plastic (Fig. 2). The inside dimensions are twenty-three inches long, two inches wide, and four inches deep. The tank rests at the open top end of the model. Four aluminium tubes project from one end of the reservoir tank. The tubes have an inside diameter of 5/32-inch and are spaced 3/4-inch apart with the bottom one, 1/4-inch above the reservoir bottom. One of the tubes was used for inlet of water. Any of the remaining tubes could then be used for overflow of water. Consequently, the amount of head in the reservoir could be controlled by the choice of tubes. The minimum head allowable was 1/4-inch, whereas the maximum



Infiltration Tank

FIG. 1



Reservoir Tank

Fig. 2

head was 2 1/2-inches. Water dripped from the reservoir into the model through 1/16-inch holes drilled in the bottom. Three holes are spaced equally along the reservoir bottom. Any number of holes could be drilled at any location on the bottom, if so desired. Holes not being used for a particular test were plugged with putty.

## EXPERIMENTS

The tests on the infiltration model system consisted of discharging a certain quantity of water per unit of time into the model, which was filled with clastic material. As water infiltrated, the movement of the front was marked at regular time intervals with a grease pencil on the tank front. The increments of time between successive markings varied between test runs. The purpose of this was to best depict the movement of the front so as not to have too many lines on the front of the model.

Two means of representation were used to depict the shape of the wetting front. One method was the use of photographs, whereas, the other method employed a tracing on the tank front. The latter required a reduction to page size. Both methods have their advantages and disadvantages.

Tap water was used to maintain a constant head in the reservoir tank. The tap water became partially de-aired while in the reservoir mainly because of the increase in water temperature. Although no measurements were made during these tests, de-aired water can have a marked effect on infiltration rate. Air bubbles in water can become entraped in the pore spaces of the porous media and act as a block, lowering the permeability. Before each test the discharge rate from the reservoir, per unit time, was measured. This and other data concerning each test run is contained in Table 1.

Each set up of the model was tested twice, once under dry conditions and once under wet (water of specific retention) conditions. Before each wet test was run, the model was throughly saturated. The tank was then allowed to drain from ten to twelve hours before the test run. The same procedure was carried out for all the wet tests. Each

| Test Number | Infiltration Rate | Marking Interval For Plate | Overflow | Material | Condition | Plate |
|---|---|---|---|---|---|---|
| 1 | 15 ml/min | --- | Second Tube | Isotropic | Dry | --- |
| 1 | " | 1 min | " | " | Wet | I |
| 2 | " | --- | " | " | Dry | --- |
| 2 | " | 1 min | " | " | Wet | II |
| 3 | " | --- | " | Hetero-geneous | Dry | --- |
| 3 | " | 10 min | " | " | Wet | III |
| 4 | " | 20 " | " | Isotropic and Hetero-geneous | Dry | IV |
| 4 | " | " " | " | " | Wet | V |
| 5 | " | " " | " | " | Dry | VI |
| 5 | " | " " | " | " | Wet | VII |
| 6 | " | 6 " | " | Stratified | Dry | VIII |
| 6 | " | 20 " | " | " | Wet | IX |

Test Conditions

Table 1

wet test was stopped, once the wetting front reached the capillary fringe. The wet tests were conducted then under similar conditions throughout the model testing.

Five sets of tests were run. They ranged in complexity from an isotropic medium to a layered medium. By increasing the complexity in each successive set of tests, a particular characteristic could be studied separately and then, in the next test, in conjunction with an additional characteristic. For example, a single infiltration site was used for the first set of tests, whereas, two infiltration sites were used for the second set.

The design of the reservoir simulated the conditions of an artificial recharge pit. Under actual conditions a recharge pit would not be designed as the reservoir tank is in these tests. A "minature" recharge pit was not used in the model because the premeability of the material was too high.

Preliminary experiments showed that too high an infiltration rate confined the shape of the wetting front to a relatively narrow vertical column. For that reason an infiltration rate of fifteen milliliters per minute was used.

For the first set of tests three and one-half feet of Ottawa Silica sand was placed in the model. The sand has an average size of .84 mm. Therefore, the model very nearly simulated an isotropic aquifer. Some stratification was produced as the tank was filled with sand but the effects during infiltration were very minor, however, in both the dry and the wet isotropic tests as a result of the stratification.

This first set of tests served to point out the general shape of the wetting front during infiltration. An obvious difference could be noted between the wet and dry isotropic tests. In the dry test, water moved away from the infiltration site more rapidly in the vertical direction than in the horizontal. In the wet test, the retained water in the sand afforded more lateral movement of the wetting front (Plate I).

Each test on the model determined a characteristic that could be applied to an actual recharge pit. In the first tests, a comparison was made between the spread of the wetting front in the model as compared to situations where material underlying an artifical recharge area are very nearly dry and when it has some retained water. If the material beneath the recharge pit is dry, the infiltration front will produce a narrow column of wetted material extending from the pit to the water table and apparently subsequent flow (infiltration) will occur along this zone. If the deposit is already wetted or when it becomes so, the wetting front will spread laterally more than it will move vertically. Thus in the recharge area, the spacing of pits will have to be strategically located so as to provide maximum efficiency for the available water. A period of time at the beginning of operations will be inefficient until the area between the pit and the water table becomes wetted. Pits should be spaced on the basis of how the system will operate after the area beneath the pit has been wetted and is flowing.

The purpose of the second set of tests was to study the effect of two indiltration sites. Again the tests were conducted using Ottawa sand. As in the first tests, the wetting front in the dry test moved vertically downward more quickly than when the sand was wet. The wetting fronts from the two sites, in both dry and wet tests, had no effect on each other until they coincided (Plate II). At which point, the combined fronts spread out from each other laterally. The reason for this was that they could no longer spread laterally toward each other. Had the tank been wider, the movement of the fronts could have been realized to a greater extent.

Consequently, in the second tests optimal spacing between recharge pits was studied. It is important to denote here that as the material for some distance under and surrounding the pits becomes wetted, the volume of material wetted begins to reach a constant amount. To ascertain the correct spacing of pits, the depth to the water table seems to be most critical. Assume the flow to be nearly unobstructed by lenses of material of different permeability, then as the depth to the water table increases, the pits should be spaced more closely because of less lateral spread. Obviously, the more pits the greater the volume of water that could be introduced underground. But, cost of construction is a limiting factor. So efficient locations for the pits is of prime importance.

The third set of tests consisted of mapping the wetted front as it infiltrated through material ranging in size from fine sand (1/8-1/4 mm) to pebbles (5 mm). The sample material was collected from a gravel pit just northwest of the intersection of Frank Road and Interstate 71 in Columbus, Ohio. The sample came from several lenses about ten to fifteen feet below the top of the pit. The lenses are glacial outwash.

The tank was filled with three and one-half feet of the channel material. It was unsorted and unstratified. Once again the same relative differences were noted between the wet and dry tests. Lateral spread of the front in both the wet and dry tests became more predominate than in any of the previous tests. The lateral spread can be attributed to increased capillary action in the smaller size ranges of the sample. Plate III depicts the pattern of infiltration for the wet test which had a more even shape than the dry test.

As can be seen from the third set of tests, the size and distribution of material is also of prime importance.

Detailed sampling of the subsurface geology is needed. The areal extent and thickness of the material above the water table must be mapped. Permeability tests should be run to determine the maximum rate of infiltration that will be possible with a certain head. It would be nearly useless, for example, to place the recharge pit in a clay pit relative to placing it in a sand deposit.

The fourth and fifth set of tests had one and one-half feet of Ottawa sand and one and one-half feet of the channel material. In the fourth tests the channel material was overlain by the Ottawa sand. In the fifth tests the positions of the sample were reversed.

The shape of the dry test (Plate IV) in the fourth set of tests reflects a change in wetting front shape. The wetting front moved down normally until it reached the interface between the two materials. At that point, the front did not cross the interface but moved out laterally. Then the front crossed the interface and moved downward much more rapidly in the channel material than it had in the sand. There was very little lateral movement of the front in the channel material. In the wet test (Plate V) of the fourth set, the same phenomenon (as in the dry test) was recorded.

From the fourth and fifth tests, it can be seen that the change in grain size from one bed to the underlying one is of considerable significance. A change in shape of the wetting front occurs at an interface between material of different sizes. Given a field situation where fine material overlays coarse material, the finer material will limit the vertical flow. Consequently, more pits would be required in this situation than those areas where finer material is overlain by coarser. With coarser material on top, one pit could have an infiltration rate that could only be equaled by possibly several pits if finer material was on top. Here again the importance of mapping and permeability tests must be stressed.

Layered material of various sizes composed the sixth set of tests. The previously unsorted material was sieved into four sizes: 8 mesh, 10 mesh, 18 mesh, and 35 mesh. These correspond to beds: 2, 4, 6, and 8, respectively. The tank held in ascending order, Ottawa sand (bed 1) on the bottom, bed 2, Ottawa sand (bed 3), bed 4, etc. with Ottawa sand (bed 9) on top (Plate VIII and IX). Bed 2 was four inches thick, bed 4 three inches thick, bed 6 two inches, and bed 8 one inch. Due to the difficulty of viewing the moving front, dye was mixed with the infiltrating water. Since the dye-water solution was mixed prior to each test, the solution may have contained less dissolved gas than was present in previous tests.

As water infiltrated during the dry test (Plate VIII), it moved rapidly downward through bed 9 with only slight lateral spread. Upon reaching bed 8, however, downward movement was temporarily halted. The water spread out along the interface saturating the lower part of bed 8.

The water crossed the bed 9-8 interface when the head became sufficiently large. Once the water entered bed 8, lateral movement in that bed became quite rapid. The water crossed the bed 8-bed 7 interface after head had increased sufficiently. After passing through the next bed (bed 7), less head was required to cross the bed 7-bed 6 interface than was necessary for the bed 9-bed 8 interface. The reduction in head necessary can be attributed to the close similarity of size between the Ottawa sand and bed 6. The head required to cross the bed 5-bed 4 interface was more than any of the upper previous interfaces. Water spread laterally only to a small degree in bed 4. When water passed through bed 4, it did so rapidly. The water, next, began to saturate bed 3. Total saturation of this and the Ottawa sand in the above layer was nearly complete when the water broke through the bed 3-bed 2 interface. The water penetrated bed 2 more rapidly than the others. No lateral movement occurred in bed 2.

After six hours of operation, total saturation had not occurred in the bottom bed (bed 1) or in beds 8, 6, 4, or 2. Only the remaining Ottawa sands (beds 9,7,5,&3) had become saturated due to capillary action. Bed 8 had more of its volume saturated than bed 6, 6 more than 4, and 4 more than 2.

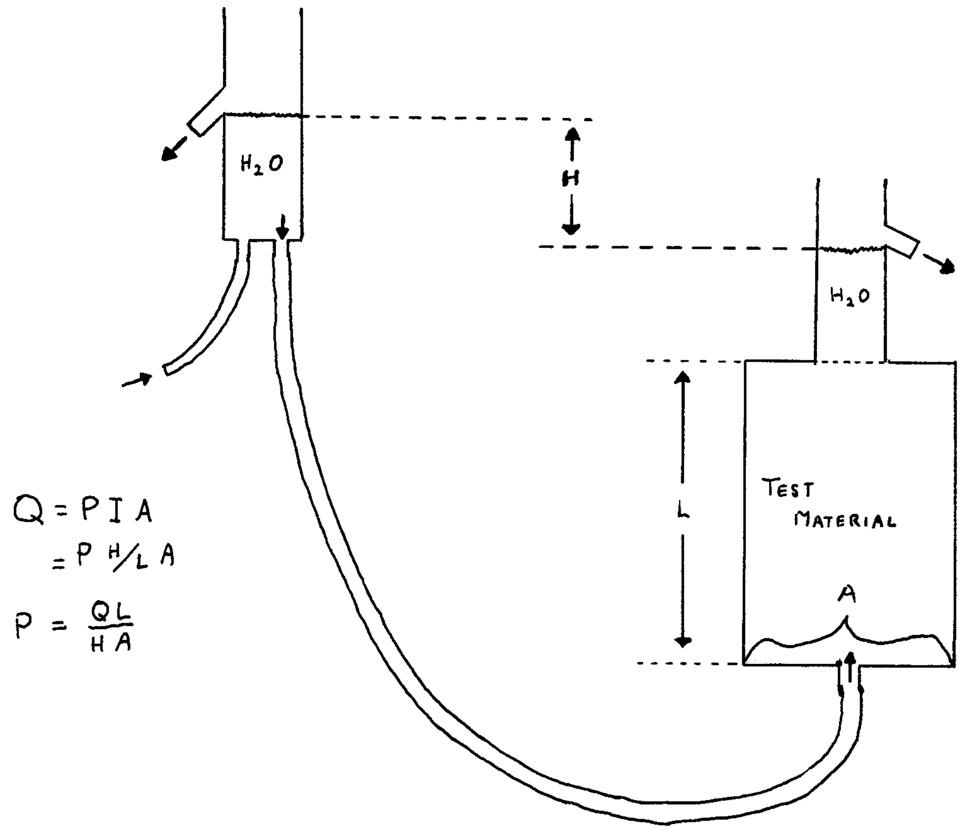
In the sixth set of tests, the importance of knowing what the material is and its vertical and horizontal extent is demonstrated. The movement of water through the stratified material contained in the model provides a visual means of observing and measuring all the characteristics, of flow beneath a recharge pit, interacting with each other.

ADDITIONAL TESTS

In order to better understand the movement of fluids through the various materials used in the testing; several hydrologic parameters were measured, such as, permeability, porosity, specific retention and specific yield (Table 2). A constant head permeameter was used to measure the permeability (Figure 3). The construction and operation of the permeameter is contained in Johnson 1963. For the measurement of porosity, specific retention, and specfic yield only the sample tube of the permeameter was used (Figure 4). Connected to that tube was an apparatus which measured the volume of water introduced and drained from the sample. Porosity is that volume of water which filled the tube containing the sample, i.e., the void space between sample grains. Specific yield is the volume of water which drained out of the tube due to gravity. The difference between the porosity and the specific yield results in the specific retention.

| Bed | Permeability | Porosity | Specific Yield | Specific Retention |
|---|---|---|---|---|
| 8 | 2285 gpd/ft$^2$ | 39.5 % | 2.2 % | 97.8 % |
| 6 | 2101 " | 33.1 " | 48.7 " | 51.3 " |
| 4 | 1195 " | 41.3 " | 67.3 " | 32.7 " |
| 2 | 375 " | 42.5 " | 78.6 " | 21.4 " |

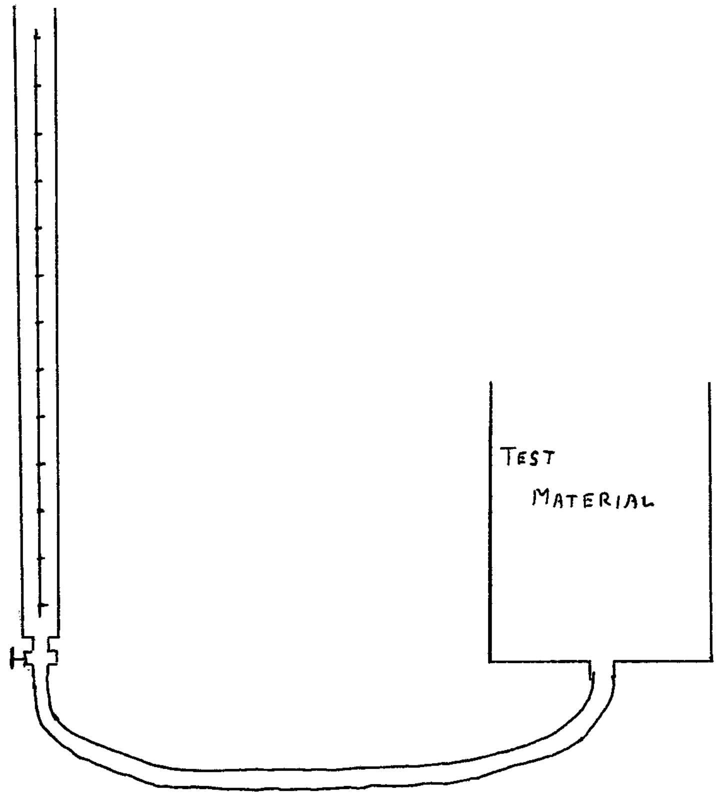
Table 2




Constant Head Permeameter

Figure 3

All of the measurements utilized de-aired tap water. Temperature corrections were made using the standard table (Johnson 1963). Due to the nature of the testing, the specific yield and the specific retention were measured only for a period of thirty minutes. The generally accepted period of measurement is twenty-four hours. A longer drainage period would have resulted in a higher yield for the finer material but very little change for the coarsest material. No doubt, inaccuracies in the retention and




Apparatus for Determining
Porosity, Specific Retention
and Specific Yield

Figure 4

yield also occurred due to the short length (six inches) of the sample tube. A short column does not allow a natural equilibrium to develop.

## CONCLUSION

The dry tests simulated conditions found above the water table. Of course extremely dry conditions, as the dry tests were, are not ordinarily the case in areas having a humid climate or in areas with a water table near land surface. The wet tests simulated conditions near the water table in the capillary fringe. It is analogous to a zone of infiltration where the water table has been recently lowered and only a minimum amount of gravity drainage of the deposits has occurred.

If a field situation could be duplicated in the laboratory model, quantative data could be calculated which would allow precise planning and operation of the recharge pit based on the qualatative flow characteristics determined in this report.

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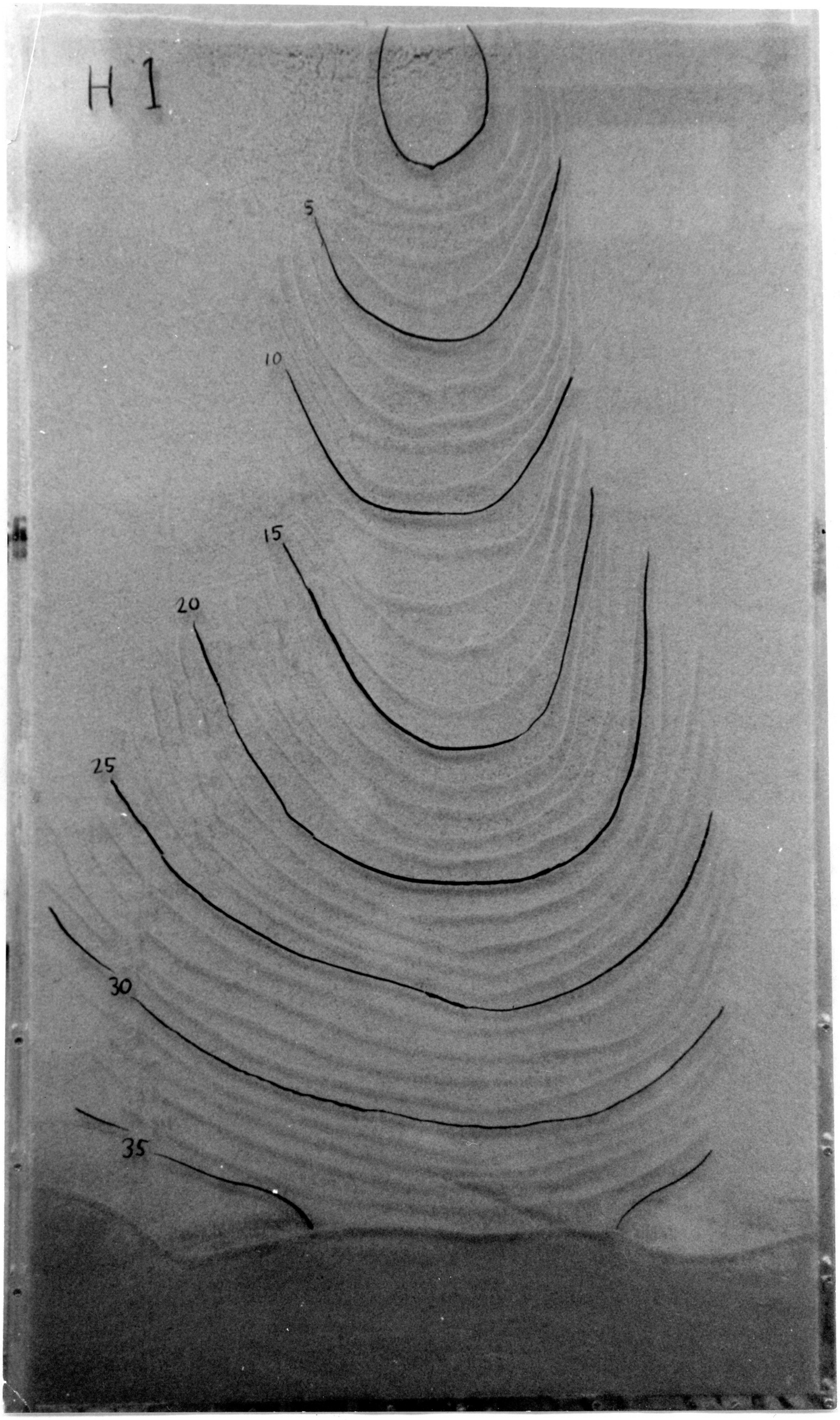
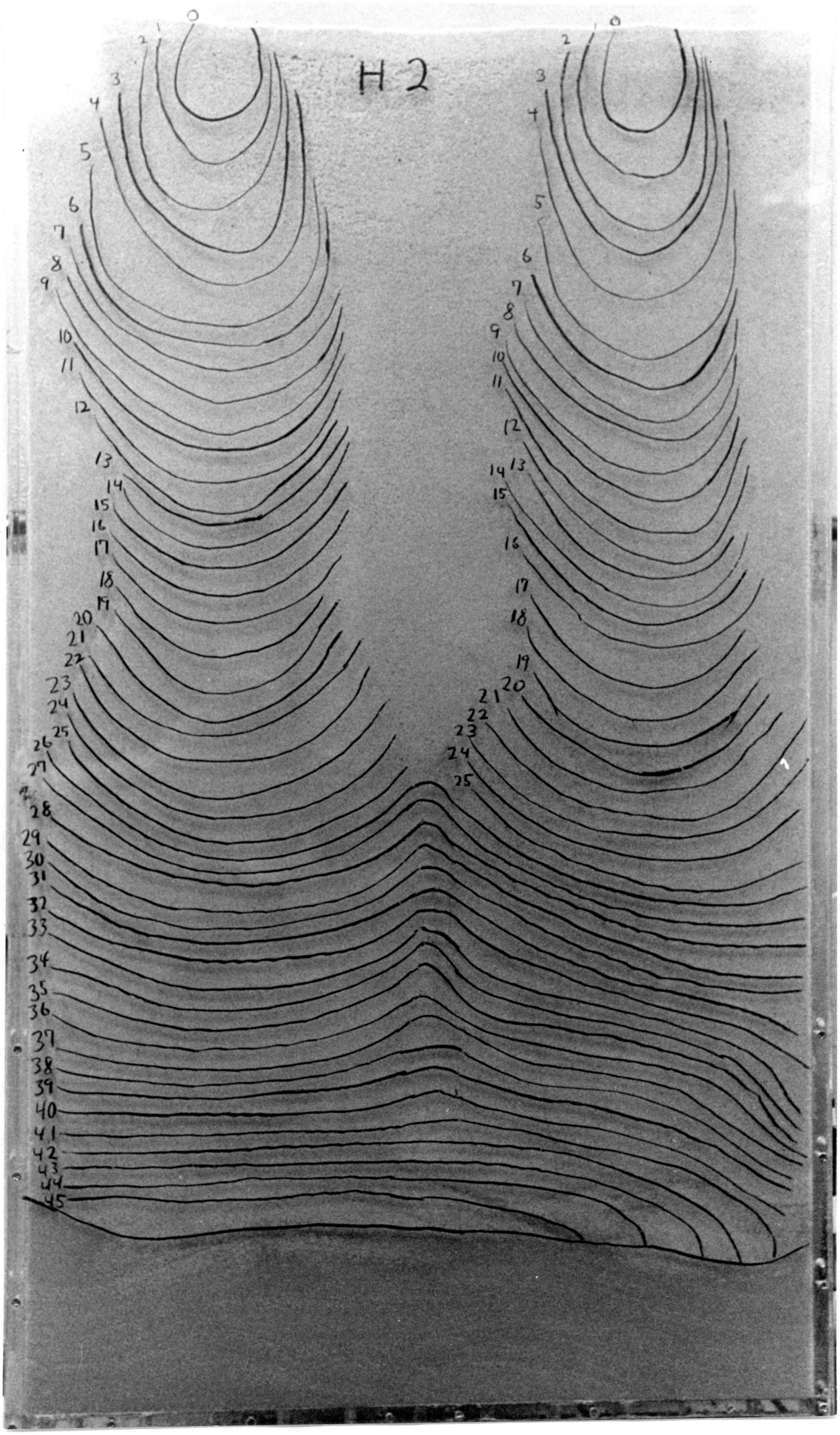
Plates I - IX




Wet Isotropic Test 1

Plate 1

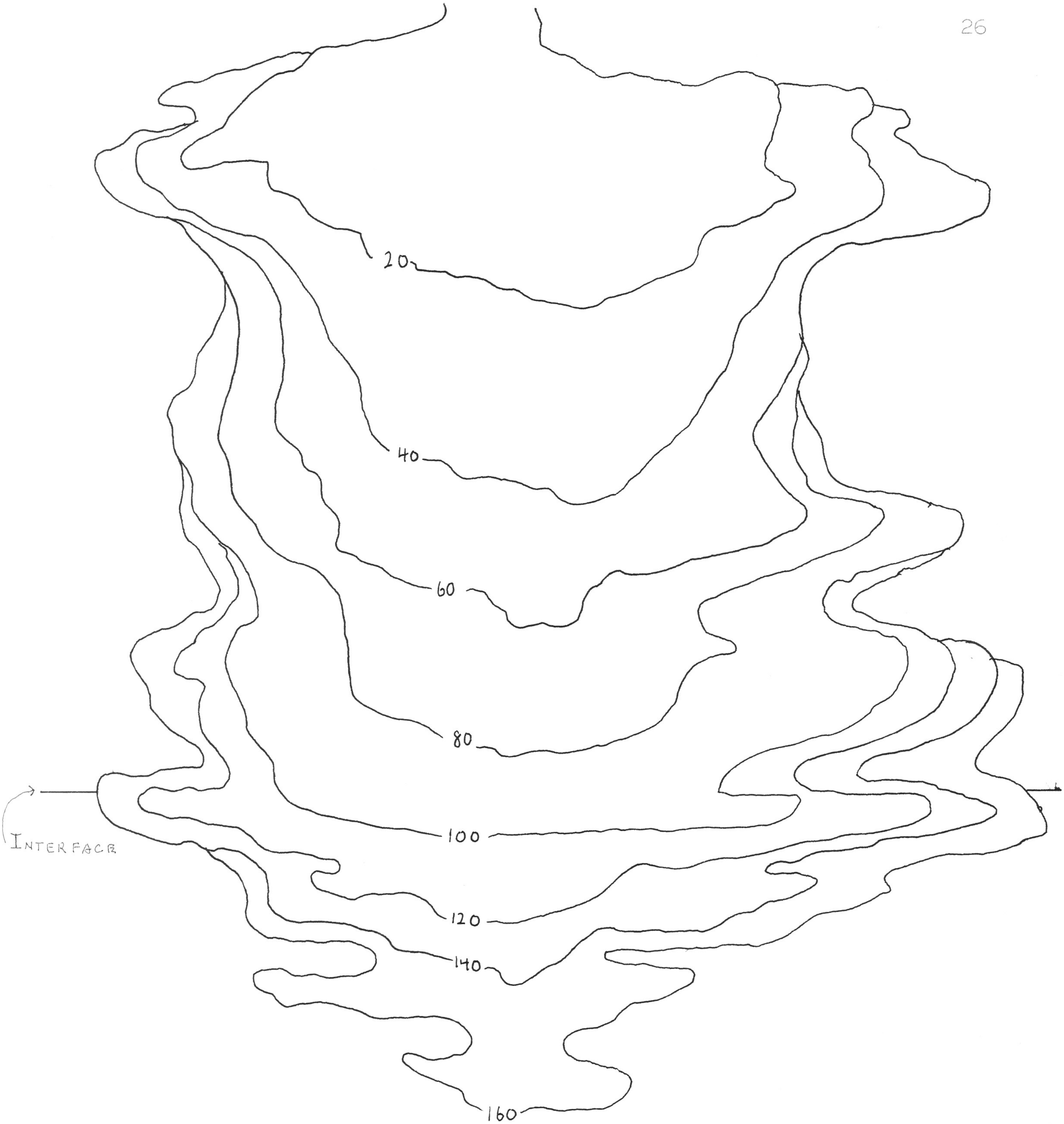



Wet Isotropic Test 2

Plate 2

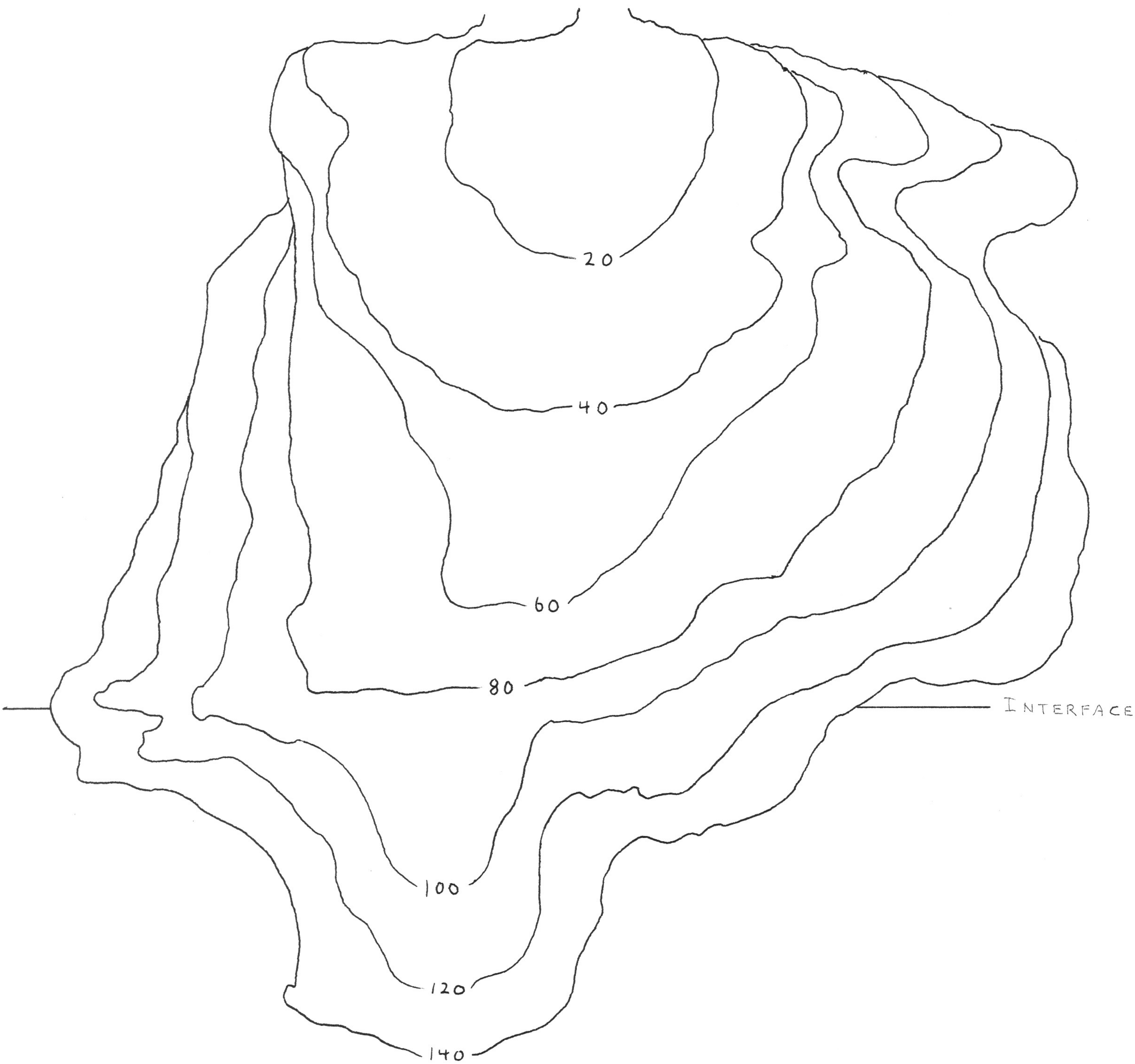

Wet Heterogeneous Test 3

Plate 3



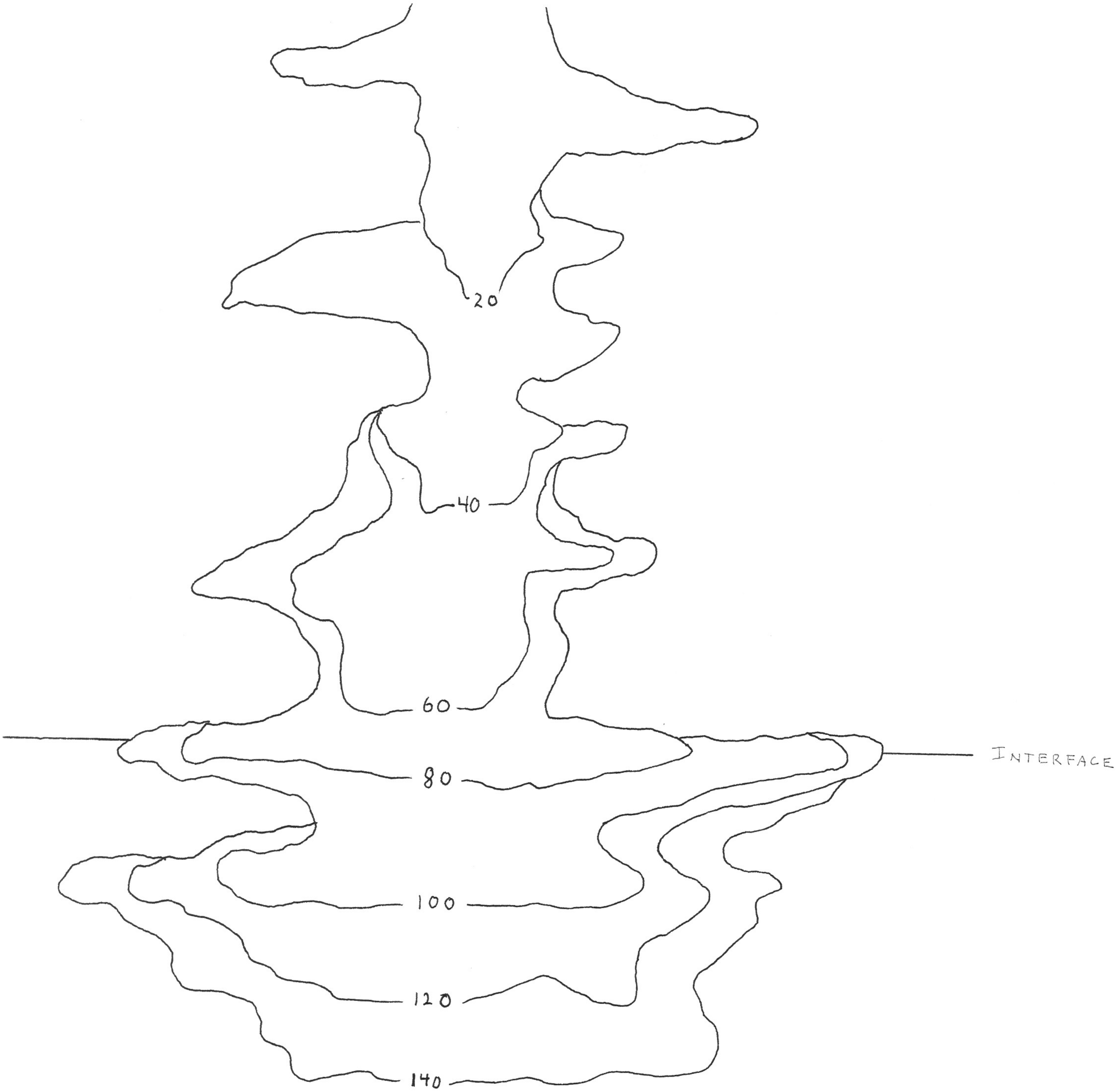

Dry Isotropic and Heterogeneous Test 4

Plate 4

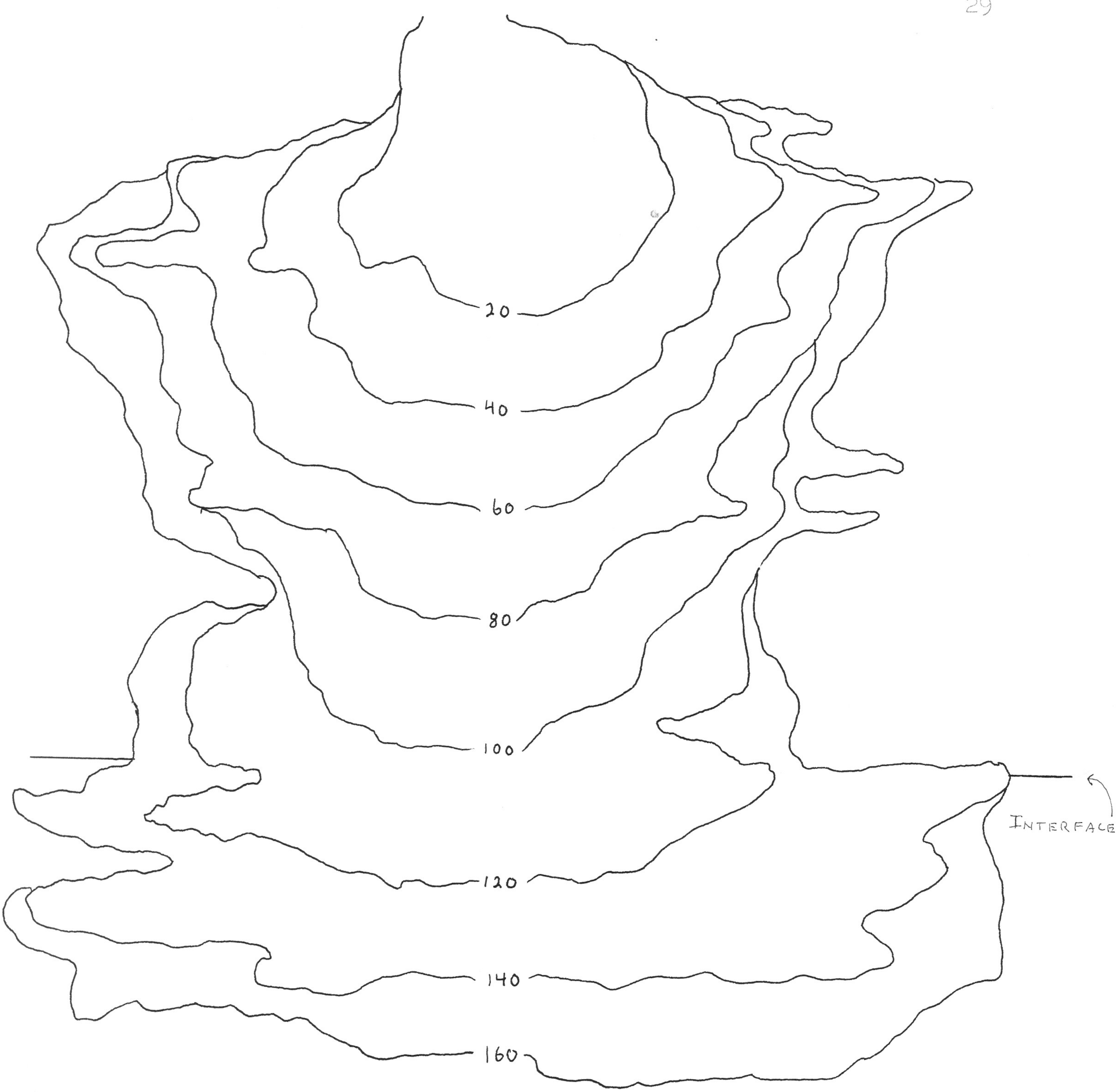



Wet Isotropic and Heterogeneous Test 4

Plate 5




Dry Isotropic and Heterogeneous Test 5
Plate 6




Wet Isotropic and Heterogeneous Test 6

Plate 7

BED 9

8

7

6

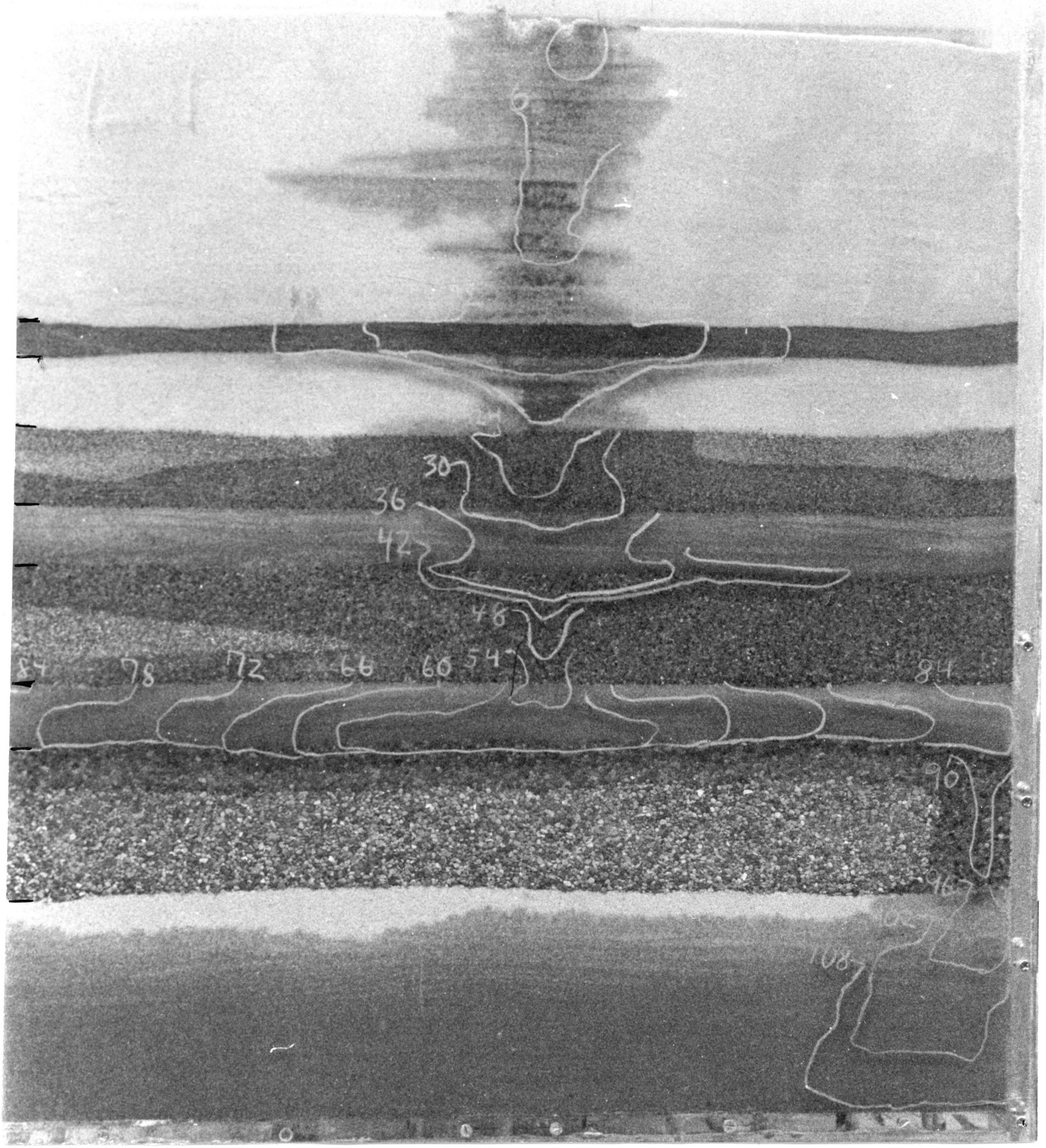
5

4

3

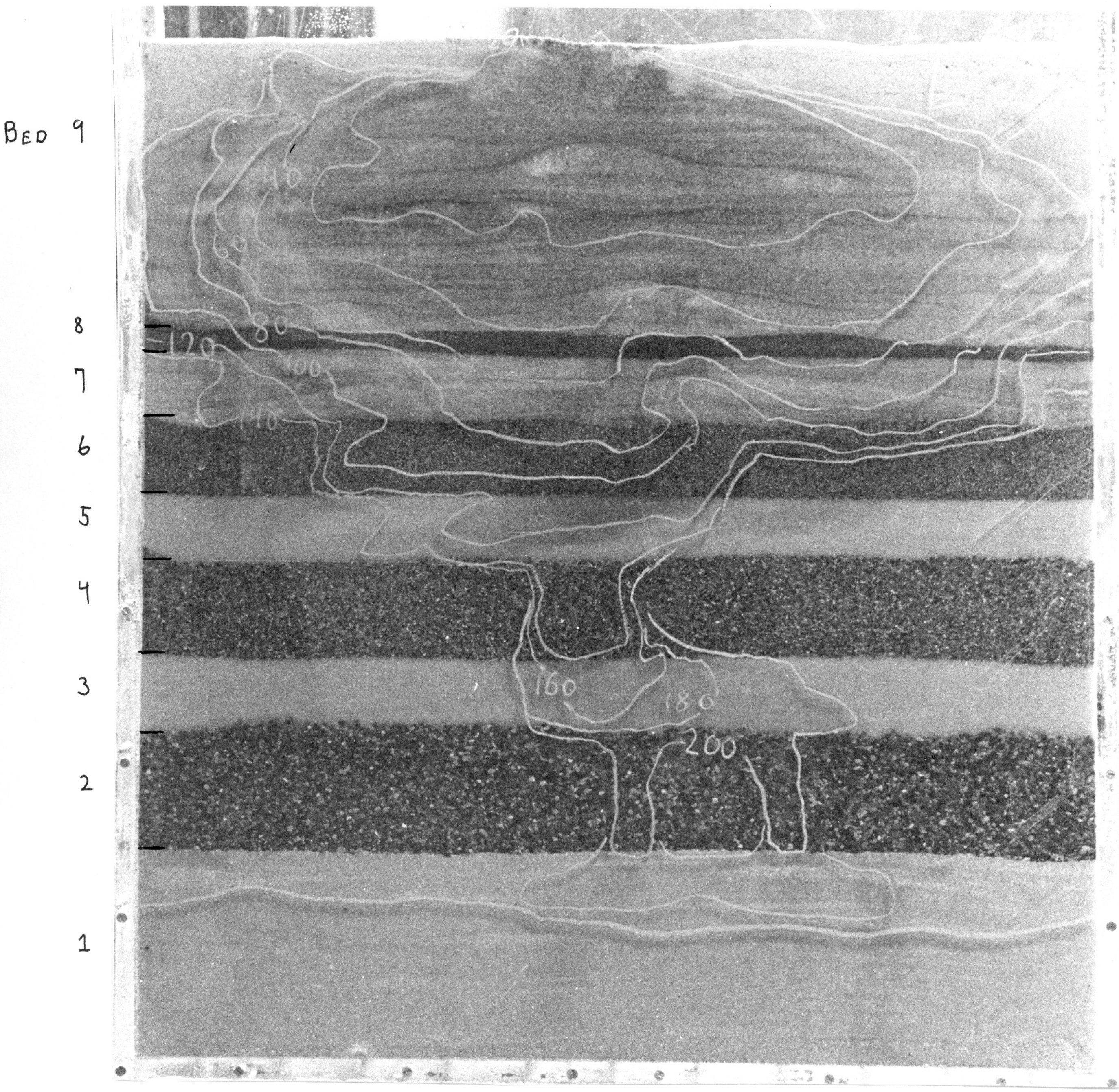
2

1




Dry Stratified Test 6

Plate 8




Wet Stratified Test 6

Plate 9